A Digital Twin-Enabled Approach to Optimize Freight Fleet Operations in a Peruvian Transportation Company

Deyber Flores Cabezas, Liset S. Rodriguez-Baca
Professional School of System Engineering, Cesar Vallejo University, Lima, Peru

***Abstract*—The study evaluates the impact of a system enabled by Digital Twin on the optimization of the operations of a cargo fleet belonging to a transport company in Lima, Peru, during the year 2025. The proposed solution integrates OBD-II sensors, a Python processing engine, and a MongoDB-based data layer to build a synchronized virtual representation of 25 operating vehicles. An experimental, pre-experimental design with measurements before and after the intervention was applied to analyze changes in the frequency of accidents, the use of load capacity, and the monthly number of trips. The results show significant improvements: the frequency of accidents decreased from an average value of 0.08 to zero; the use of load capacity increased from 31 to 35 units; and the number of trips required to transport equivalent volumes decreased. These findings suggest that Digital Twin–based systems can support safer, more efficient, and data-driven operations in emerging logistics environments.**

***Keywords*—Digital Twin; fleet management; IoT; transportation; operational optimization**

I. INTRODUCTION

Freight forwarding companies are operating in rapidly changing conditions today. The pressure to comply with stricter schedules, maintain operational security, and make better use of resources requires constant coordination between people, vehicles, and processes. However, in many regions and more frequently in emerging economies, decisions continue to depend on partial systems or fundamental digital tools, which limit the ability to foresee contingencies or adjust operations in time [1], [2]. When the environment becomes more dynamic, and cargo volumes increase, these limitations translate into delays, greater wear and tear on the units, and a reduced margin to react to unforeseen events [3], [4].

In recent years, the idea of virtually representing a physical process through a Digital Twin (DT) has gained prominence as an alternative to face these challenges. A DT combines real-time data with models that enable interpretation of a system's state and anticipation of its behavior. Thanks to the integration, it is possible to observe the performance of a vehicle, a production line, or even an entire logistics network in a virtual environment that reflects what happens on the physical plane [5], [6], [7]. The technology, applied correctly, facilitates the early detection of failures and allows exploring how a system would respond to different scenarios before executing them in real operation.

While most studies have been conducted in highly automated facilities or in projects linked to autonomous driving, the principles underpinning DTs can also be applied in traditional fleets operating with modest technological resources [8], [9], [10].

In the transport of goods, having timely information on the vehicle's driving, mechanical condition, and use can make the difference between an efficient service and an expensive or risky one. When control is based solely on manual observations or incomplete reports, it becomes difficult to detect driving patterns that can lead to incidents, identify route deviations, or assess whether the load is being used properly. A DT offers a way to overcome these limitations by collecting continuous telemetry and converting it into indicators that support operational decision-making.

Despite this potential, there is still little evidence on DT implementations in small and medium-sized transport companies in Latin America. Many of them work with tight budgets and limited digital infrastructure, so it is essential to explore lightweight, cost-effective, and open component-based solutions that can be tailored to their needs. It is necessary to show that this type of technology can generate added value in safety and operational efficiency without requiring a high investment.

To address this need, a DT was implemented in a Peruvian freight transport company. The IT solution combines OBD-II sensors, Python microservices, a document-oriented database, and a real-time monitoring panel. Its effect is measured using an experimental, pre-experimental design, with three key indicators: accident frequency, load capacity use, and the number of trips required to meet demand. Taken together, the results point to meaningful improvements across all indicators and suggest that an accessible DT architecture can help strengthen safety and operational efficiency, even in companies with limited technological resources.

The article is organized according to the following sections: Section II summarizes the main contributions; Section III contains linked antecedents; Section IV explains the methodology and architecture of the IT solution; Section V presents the findings of the research; Section VI presents the discussion; Section VII presents the conclusion, and Section VIII outlines future work.

II. RESEARCH CONTRIBUTION

The study identifies three aspects that help explain how Digital Twins (DT) can be applied in transport companies operating with limited technological resources.

- The first contribution is a DT architecture that operates without costly equipment or complex technological platforms. The proposal for the study uses affordable OBD-II sensors, open-source tools, and microservices that operate in a modular way, thereby avoiding reliance on specialized technological equipment.
- The study explores the effect of Digital Twin technology on the day-to-day performance of a freight transport company. While Digital Twins are already common in industrial and automation environments, their application in traditional fleets remains less studied. For that reason, three key indicators—accident occurrence, load capacity utilization, and number of trips—were compared before and after the implementation of the IT solution. The results made it possible to observe how continuous monitoring and data-driven analysis derived from the DT can contribute to safer and more efficient fleet operations.
- The study proposes a simple methodology. The methodology combines data capture via IoT devices, continuous information processing, and a set of indicators that can be adapted to different types of organizations. In addition to addressing the needs of the company analyzed, the framework serves as a guide for researchers and others interested in implementing DT in SMEs.

These contributions show that Digital Twins can be effectively applied in the transport sector, even in organizations that have had difficulty adopting more advanced technologies. The results obtained show that, even with low-cost solutions and reduced scale, it is possible to achieve clear improvements in operational performance. These results also open the door to new lines of research aimed at refining lightweight architectures and exploring their application in broader and more complex scenarios.

III. RELATED WORK

In recent years, having a digital replica of a physical system has come to the forefront across various areas of engineering. The Digital Twin approach makes it possible to understand how a real process may behave and to anticipate possible operational situations. Although its use has been consolidated in industries with high levels of automation, in cargo transport, it is still in an exploratory stage, where companies seek to adapt their principles to the particularities of their operations.

Wang et al. [13] presented a vehicle navigation prototype based on a Digital Twin model, which improved the accuracy of automated decisions. The authors showed that by maintaining a constant flow of data between the vehicle and its virtual representation, it is possible to anticipate potentially dangerous maneuvers and correct them before they lead to an accident. That conclusion is relevant to the present study because it highlights an important point: when information is analyzed in real time, it becomes a valuable resource for reducing unwanted operational events.

Tang et al. [14] emphasize that Digital Twins must adapt to the environment in which they are implemented. According to their analysis, a generic architecture does not always yield reliable results, as each domain has specific conditions that must be reflected in the virtual model. Such an observation is especially relevant in cargo transport, where operating conditions change frequently and vehicles do not always have the same equipment or receive the same level of maintenance.

It is also relevant to mention the contributions from the industrial field. Ramasubramanian et al. [15] studied how Digital Twins support collaboration between operators and robots in a production plant. Although their work is not focused on logistics, they use Digital Twins to create a virtual representation that enables them to analyze different operational alternatives without interrupting the real process. Such an approach reduces both the risks and the costs associated with direct experimentation in the physical environment.

In the logistics field, Abdullahi et al. [16] developed a framework to improve sustainability by combining Digital Twins with real-time operational data. Their findings showed that increased digitalization enables more precise route planning, avoiding unnecessary travel and reducing both fuel consumption and emissions. A closely related concern in the study is the optimization of the number of trips required for a fleet to meet the same level of demand.

Madusanka et al. [17] reviewed the use of Digital Twins in the maritime domain and identified emerging trends related to monitoring, simulation, predictive analysis, and operational decision-making. Although their study focuses on maritime environments, its findings are relevant to freight fleet management because both contexts require continuous synchronization between physical assets and virtual models to improve safety, efficiency, and resource utilization.

Finally, Gerlach et al. [18] analyzed the use of "supply chain twins" to support the management of supply chains. Their study shows that by having a digital replica of each stage of the process, organizations can more clearly understand how the whole behaves and make informed decisions. This perspective supports the idea that a Digital Twin, even in smaller-scale operations or with limited resources, can deliver tangible improvements in efficiency and safety.

The revised precedents coincide in two central aspects. On the one hand, they argue that Digital Twins are a powerful tool for optimizing operational performance. On the other hand, they highlight the lack of research conducted in real-world settings, especially in environments with limited technological infrastructure. The present study addresses that gap by testing a simple, low-cost architecture in a Peruvian freight transport company.

IV. METHODOLOGY

A. Study Design

The study adopted a quantitative approach and an applied purpose, aiming to determine how a technological intervention could influence the operational performance of a freight transport company. A pre-experimental design was used, with measurements taken before and after the system's implementation. A design of this kind is appropriate when the goal is to examine changes associated with an innovation without full control over the external variables that affect daily operations.

Under this design, it was possible to directly identify the effect of the Digital Twin on indicators used by the company in its usual management, without altering the real context in which its activities take place.

The evaluation process lasted three months, during which the initial data and post-commissioning measurements of the technological solution were collected. The interval was selected to ensure the operational stability of the fleet and reduce the influence of external variations such as high seasons or changes in transport demand.

Although the pre-experimental design allowed direct comparison of operational indicators before and after the intervention, the absence of a concurrent control group limits strict causal attribution. Therefore, the observed improvements cannot be interpreted as being caused exclusively by the Digital Twin system, since Hawthorne effects, short-term demand fluctuations, or other operational changes during the three-month observation period may also have influenced the results.

The population consisted of the 28 active vehicles of the evaluated company. A total of 25 vehicles were selected through non-probabilistic convenience sampling because they had fully functional OBD-II sensors and availability for continuous monitoring. Although a probabilistic method was not used, the sample represents 89.2% of the total fleet, providing high representativeness for the analysis.

The selection was justified by operational criteria: vehicles in continuous use, stable routes, and engines compatible with standard telemetry. The selection criteria made it possible to collect consistent and comparable data across both phases of the study.

B. Digital Twin Architecture

The architecture developed for the study was designed with a lightweight, scalable approach, leveraging low-cost technologies and open-source tools with high interoperability. The architecture is composed of four functional layers:

- IoT Layer (Data Capture): Integrated by OBD-II sensors installed in each vehicle, responsible for recording operational telemetry such as speed, acceleration, engine temperature, fuel consumption, and braking patterns. These data were transmitted wirelessly to the central server.
- Processing Layer (Microservices): Implemented in Python using the Flask framework. It included modules for data cleaning, outlier detection, unusual event identification, and daily indicator aggregation.
- Storage Layer (Database): MongoDB was chosen for its ability to manage both structured and unstructured data and for its flexibility in handling large volumes of telemetry. The database stored historical records, processed indicators, and instantaneous fleet statuses.
- Visualization Layer (Real-Time Dashboard): Developed to display processed information through graphs, alerts, and operational indicators. This layer simulated the fleet's behavior, enabling monitoring of trends, routes, critical events, and variations in load capacity.

Fig. 1 shows that the layers comprise the functional version of the Digital Twin, capable of synchronizing the physical and virtual states of the vehicles during their real operation.

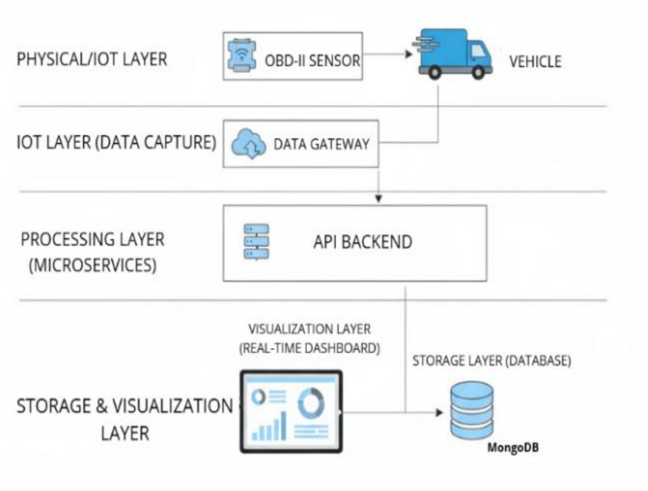

Fig. 1. Architecture of the lightweight Digital Twin system integrating OBD-II telemetry, microservice-based processing, a document-oriented database, and a real-time monitoring dashboard.

C. Procedure for Data Collection

The data collection process followed the following stages:

- Installation and calibration of OBD-II sensors in the 25 selected vehicles.
- Continuous telemetry record stored every 2 seconds throughout the study period.
- Data integrity validation, discarding corrupted or inconsistent values.
- Raw data processing, generating daily indicators per vehicle.
- Consolidation of operational indicators: frequency of accidents, load transported, and number of trips made.

The general data collection and processing workflow is presented in Fig. 2, which summarizes the sequence from sensor installation and telemetry acquisition to data validation, indicator generation, and operational analysis.

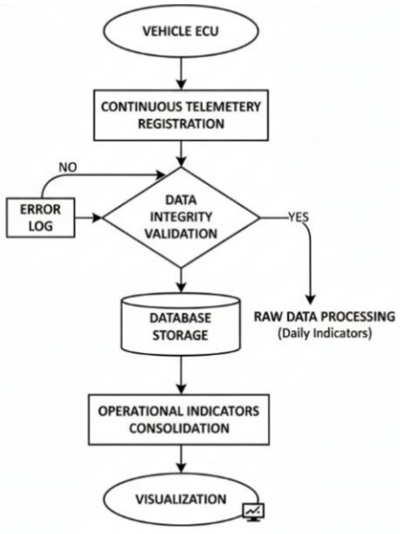

Fig. 2. Flow chart and processes.

The study focused on three key indicators:

- Accident frequency: number of incidents recorded per vehicle during the evaluated period.
- Load capacity use: average number of units transported per trip.
- Monthly number of trips: total trips needed to meet standard demand.

These indicators were selected for their direct relevance to efficiency, safety, and logistics performance.

D. Event Detection Module

The event detection module is responsible for identifying risky driving behaviors based on the telemetry received. It processes each new sample from the OBD-II device and evaluates a set of thresholds for speed, acceleration, and braking intensity. When one or more thresholds are exceeded, the module generates an event log that is stored in the database and displayed on the control panel as a security alert. Algorithm 1 summarizes the logic implemented in the event detection microservice.

Algorithm 1: Event Detection Module

```
Input: telemetry sample s = {speed, rpm, throttle, brakeForce, gpsPosition, timestamp}
Parameters:
SPEED_LIMIT = 90 km/h
ACC_THRESHOLD = 3.0 m/s² // harsh acceleration threshold
DECEL_THRESHOLD = 3.5 m/s² // harsh braking threshold
TEMP_LIMIT = 95 °C // engine temperature alert threshold
Output: list of detected events E
Begin
E ← ∅
//Overspeeding
    if s.speed > SPEED_LIMIT THEN
        E ← E ∪ {("OVERSPEED", s.timestamp, s.gpsPosition)}
    End if
// Harsh acceleration
    if s.acceleration > ACC_THRESHOLD then
        E ← E ∪ {("HARSH_ACCELERATION", s.timestamp, s.gpsPosition)}
    end if
// Harsh braking
    if s.brakeForce < −DECEL_THRESHOLD then
        E ← E ∪ {("HARSH_BRAKING", s.timestamp, s.gpsPosition)}
    end if
//Engine temperature alert
    if s.engineTemp > TEMP_LIMIT then
        E ← E ∪ {("HIGH_ENGINE_TEMPERATURE", s.timestamp, s.gpsPosition)}
    end if
return E
End
```

For the monitored fleet, the thresholds were set at 3.0 m/s² for harsh acceleration, 3.5 m/s² for harsh braking, and 95 °C for engine temperature alerts during the calibration stage of the system.

TABLE I. SYSTEM AND DATA ACQUISITION PARAMETERS

Parameters	Value
Number of vehicles monitored	25
Sensor Type	OBD-II (ELM327-based)
Telemetry frequency	1 sample/2 seconds
Data transmitted	Speed, RPM, throttle %, fuel rate, engine load, braking intensity
Transmission protocol	Bluetooth / WiFi
Database system	MongoDB (document-oriented)
Processing pipeline	Python microservices
Monitoring dashboard	Web-based (real-time)

Table I clearly shows how the system supporting the Digital Twin was configured. The company worked with a fleet of 25 units, each equipped with an OBD-II sensor capable of sending data at a short periodicity, sufficient to track vehicle behavior in near real-time.

The values collected provide a relatively complete view of each unit's state, ranging from basic variables such as speed to indicators of engine effort and the driver's brake use. All that information was transmitted wirelessly to a database designed to handle large volumes of records, where small Python modules then processed it.

The entire flow was integrated into a visualization panel that allowed for the review of the fleet's activity while it was in operation.

E. Monitoring Dashboard

In addition to data acquisition and processing, the proposed system includes a web dashboard that provides real-time visibility into fleet operations. The dashboard is organized into three main panels: a map view showing the current GPS position of the selected vehicle, a telemetry panel showing key indicators such as speed, engine temperature, and battery voltage, and an event panel listing active safety alerts.

Supervisors can filter events by vehicle, adjust the refresh rate, and toggle between the live and historical views. The interface allows operating personnel to monitor driving conditions during trips and review past events for training or audit purposes.

Fig. 3 shows a capture of the panel used to monitor the fleet in real time. There, you can see the vehicle's location, the central telemetry values, and the alerts generated during the operation.

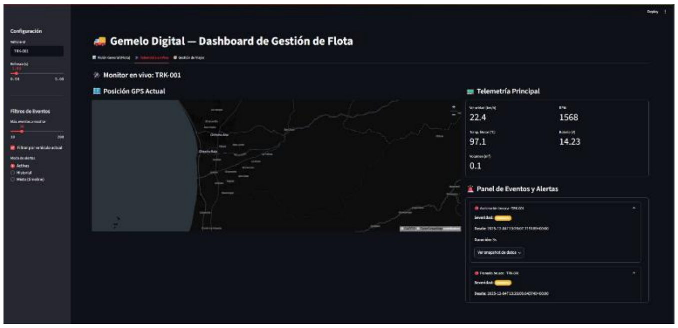

Fig. 3. Digital Twin–based fleet monitoring dashboard showing live GPS position, key telemetry indicators, and active safety alerts.

F. Statistical Analysis

T-tests were applied for related samples to compare the pre-test and post-test values of the three operational indicators. The significance level was set to $\alpha = 0.05$. The test was adequate given the continuous nature of the data and the comparison between two observation times for the same sample.

Likewise, descriptive measures such as averages, standard deviations, and percentage variations were used to complement the interpretation of the Digital Twin's impact. Additionally, basic assumptions, such as the normality of the differences, were verified through graphical and statistical analyses.

For the study, no routes, loads, or activities that could affect driver safety or the integrity of vehicle units were manipulated.

Regarding internal validity, efforts were made to control factors that could influence the results, such as changes in demand, route adjustments, or changes in fleet composition. Regarding external validity, it is recognized as limited; however, the procedure followed can be reproduced in companies operating under similar conditions, opening the possibility of applying the methodology in other contexts within the same sector.

V. RESULTS

The incorporation of Digital Twin enabled unambiguous identification of changes in the fleet's performance throughout the analysis period. The comparison between the data obtained before and after implementation provides an accurate view of how the tool influenced three central aspects of the operation: safety, load capacity utilization, and the number of displacements required to meet demand. The most important findings are detailed below.

A. Frequency of Accidents

Before the implementation of Digital Twin, the company recorded minor accidents that, although they did not always lead to material damage, did indicate potential risks. On average, the fleet had 0.08 accidents per vehicle, which indicated driving behaviors requiring attention, such as sudden braking, unexpected maneuvers, or deviations from the planned route.

After the implementation of the IT solution, the indicator improved significantly, with no accidents recorded during the post-test period. Three main changes introduced through the Digital Twin system help explain the improvement. First, continuous monitoring of each vehicle made it possible to detect unusual behavior early and respond before it escalated into an incident. Second, the alerts sent to supervisory staff created opportunities for immediate corrective action during operation. Third, drivers tended to behave more cautiously because the most relevant aspects of their driving were being monitored in real time.

The statistical analysis indicated a significant association between the intervention period and the observed improvement in fleet management indicators.

B. Use of Load Capacity

In the initial stage, the average of the indicator was 31.04 units, reflecting variations in the allocation of goods and a tendency to send vehicles with available space, especially on routes with fluctuating demand.

After implementing Digital Twin, the average increased to 35.00 units, representing a significant improvement for the operation. The variation was not due to an increase in demand, but to a more innovative use of information. The system allowed:

- Identify trips with low occupancy.
- Reorganize load allocation more evenly.
- Avoid unnecessary departures when consolidating goods is possible.

One of the most apparent effects was that supervisors could visualize each vehicle's occupancy in real time, facilitating more precise decisions when coordinating dispatches. In practice, the new monitoring process helped prevent a routine pattern in the company: sending vehicles with low loads just to meet internal schedules, even when it was not strictly necessary.

C. Monthly Number of Trips

A relevant aspect of logistics management is the number of displacements made to meet a constant demand. During the pre-test period, the number of trips tended to be higher than necessary, in part because decisions were made with incomplete information or based on estimates made at the start of each day.

Among the improvements highlighted by the operational team are:

- Fewer “empty” or underutilized trips.
- Better allocation of units by load type.
- Greater anticipation of delays or detours enabled reorganizing routes without generating additional trips.

The statistical analysis showed significant differences between the pre- and post-intervention stages, supporting the conclusion that the Digital Twin improved efficiency, reduced unnecessary travel, and contributed to lower operating costs for fuel, maintenance, and person-hours.

All three indicators point in the same direction: the Digital Twin had a positive, measurable impact on fleet operations. Not only did it improve safety and productivity, but it also offered a stronger basis for decision-making.

The results obtained show that:

- Accidents were eliminated during the post-test period.
- Use of load capacity was elevated, reducing underutilization.
- The number of trips was reduced, reflecting a more rational use of resources.

Therefore, the changes observed are consistent with the use of more accurate and timely information provided by the Digital Twin architecture. However, because the study used a pre-experimental design without a concurrent control group, these improvements should not be interpreted as being caused exclusively by the intervention. Table II shows the comparison between the pre- and post-test results.

TABLE II. PRE-TEST AND POST-TEST OPERATIONAL INDICATORS

Indicators	**Pre-test and post-test operational indicators**		
	Pre-test	***Post-test***	***Change***
Accident frequency	0.08	0.00	-0.08
Load capacity utilization (%)	31.04	35.00	3.96
Monthly trip count	250	230	-20

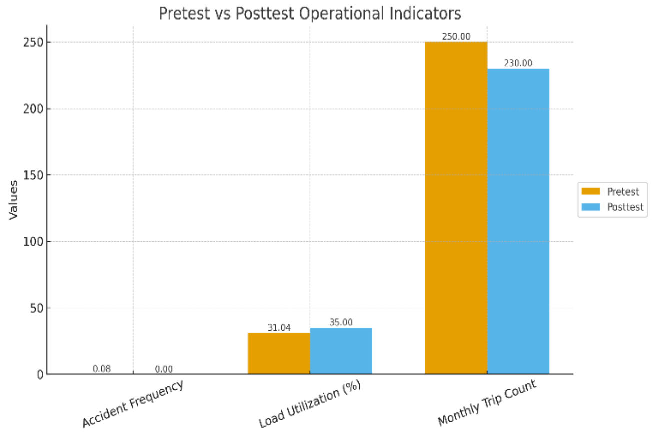

Fig. 4. Pre-test and post-test operational indicators.

Fig. 4 shows how the three operational indicators changed after implementing the Digital Twin. We can see a drop in incidents, better use of capacity, and fewer trips needed to meet the same demand.

In short, experience shows that even a company with limited resources can obtain significant benefits by adopting technologies that integrate telemetry, data analysis, and operational visualization.

VI. DISCUSSION

The results obtained allow a clearer understanding of the real impact that a Digital Twin system can have when integrated into an operating environment such as that of a freight transport company. In the first instance, the total reduction in accident frequency (from an average of 0.08 to 0.00) confirms that technology serves not only as a monitoring mechanism but also as an instrument that changes behavior and reduces risk exposure. The reduction also helped the company avoid repair costs and vehicle downtime. According to internal estimates from the head of the operations area, even a minor incident of this kind can lead to one or two weeks of service interruption for a single vehicle, in addition to direct maintenance expenses. Such findings are consistent with reports on DT-ITS systems, which emphasize the ability of Digital Twins to improve interoperability between devices, anticipate incidents, and enhance road safety through continuous synchronization between physical and virtual environments [11].

Likewise, the significant improvement in load capacity (increased from 31.04 to 35.00 units) demonstrates that the availability of reliable, real-time data enables reorganizing assignments, reducing underutilized trips, and optimizing vehicle use. The result is consistent with the findings of Moshood et al. [12], who argue that Digital Twins enhance logistical visibility, detect structural inefficiencies, and help manage critical resources within a sustainability framework. The company stopped operating on estimates and began basing its decisions on evidence.

Regarding the decrease in the number of trips (250 trips to 230), although the indicator did not decrease drastically, the difference was significant ($p = .045$). That is, as the load capacity used per trip increases, the need for additional travel is automatically reduced. Wang et al. demonstrated that decision-making based on real-time synchronized information optimizes routes, avoids redundant displacements, and improves operational efficiency in complex environments [13].

The combination of higher cargo utilization and fewer monthly trips also evidences improvements in fuel efficiency and labor use. Considering a conservative fuel cost and average driving time per route, the reduction translates into savings in fuel consumption, driving hours, and overtime pay. The implementation of Digital Twins contributes not only to safer operations but also to a gradual reduction in operating costs.

Discussion of the results is also related to experiences reported in other countries. Tang et al. [14], for example, demonstrated that combining IoT with predictive maintenance strategies reduces downtime and prevents operational failures. Similarly, Ramasubramanian et al. [15] argued that Digital Twins support strategic decision-making related to fleet management. Although both studies were carried out in more technologically advanced settings, the results of the present study suggest that Digital Twins can also deliver significant benefits in companies with limited resources.

The results show that Digital Twins are a feasible alternative for SMEs. Even without having a sophisticated technological infrastructure, it was possible to propose concrete improvements in security, performance, and resource optimization. Implementing Digital Twins can contribute not only to safer operations but also to a gradual reduction in operating costs.

The research was conducted in an SME in the freight transport sector, so the findings cannot be generalized to larger organizations with more complex processes and infrastructure. As Rigó et al. [5] point out, the performance of a Digital Twin is closely linked to the degree of technological maturity and the institutional commitment to adopting Industry 4.0 tools. These factors can vary considerably across companies.

Several factors conditioned the scope of the study. First, we worked with a single company and a small number of units, which limits the ability to extend the results to other environments with different characteristics. In addition, the implemented solution lacked more sophisticated predictive models, making it impossible to analyze long-term behavior or trends. In addition, differences in infrastructure and level of digitization between companies can influence the degree of replicability of the proposal.

VII. CONCLUSION

The findings confirm that the incorporation of a Digital Twin system had a positive, clearly observable effect on the management of the evaluated cargo fleet. The data obtained show improvements in three fundamental aspects of the operation: safety, use of load capacity, and travel efficiency. The absence of accidents during the post-test is a clear sign of the value of continuous, real-time monitoring as a tool for anticipating contingencies. Likewise, the improvement in the use of available capacity suggests that the IT solution implemented supported more accurate planning and more efficient use of resources.

A moderate reduction in the number of trips indicates that vehicle units will make fewer trips; as a result, operating costs will be reduced. The finding is consistent with prior studies that highlight the role of Digital Twins in optimizing logistics processes through the timely availability of information.

The results show that the implementation of Digital Twin technology enabled a transition from a traditional, transaction-based environment to a more data-driven setting that better supports operational decision-making. It is also confirmed that deploying an accessible solution developed with open-source tools delivers significant improvements for SMEs.

VIII. FUTURE WORK

According to the findings and limitations of the study, several lines of research are identified that could strengthen the use of Digital Twin technology in fleet management:

- Integrating machine learning with Digital Twin technology can reduce empty trips and operational failures by improving prediction and operational planning [14], [18].
- Extension of the architecture towards a complete Digital Supply Chain Twin. The studies by Gerlach et al. [18], Hakimi et al. [19] and Fatorachian et al. [20] underscore the importance of scaling Digital Twins across the entire logistics chain, not just the fleet.
- Advanced simulation of urban scenarios. Using ROS2 or AWSIM platforms would enable us to model traffic behavior and evaluate more efficient routes in real time.
- Integration with TMS and ERP systems. Connecting the DT with corporate systems would make it easier to automate load assignments, validations, reports, and prioritizations [21].

REFERENCES

[1] D. Wu *et al.*, “Digital Twin Technology in Transportation Infrastructure: A Comprehensive Survey of Current Applications, Challenges, and Future Directions,” Feb. 01, 2025, *Multidisciplinary Digital Publishing Institute (MDPI).* doi: 10.3390/app15041911.

[2] D. Nag, F. Brandel-Tanis, Z. A. Pramestri, K. Pitera, and Y. K. Frøyen, “Exploring digital twins for transport planning: a review,” Dec. 01, 2025, *Springer Science and Business Media Deutschland GmbH.* doi: 10.1186/s12544-025-00713-0.

[3] E. Markopoulos *et al.*, “The Impact of Digital Twins Technology in Maritime Fleet and Safety Management,” in *Accessibility, Assistive Technology and Digital Environments*, AHFE International, 2024. doi: 10.54941/ahfe1004619.

[4] L. J. Castillo Rabanal, A. S. Huamanchumo Gordillo, and M. A. Lecca Rengifo, “The Impact of the Application of Digital Twin Technology in Supply Chain 4.0: A Systematic Review,” *Gestión de Operaciones Industriales*, vol. 3, no. 1, pp. 80–92, Sep. 2024, doi: 10.17268/goi4.0.2024.05.

[5] L. Rigó, J. Fabianová, M. Lokšík, and N. Mikušová, “Utilising Digital Twins to Bolster the Sustainability of Logistics Processes in Industry 4.0,” *Sustainability (Switzerland)* , vol. 16, no. 6, Mar. 2024, doi: 10.3390/su16062575.

[6] U. Asad, M. Khan, A. Khalid, and W. A. Lughmani, “Human-Centric Digital Twins in Industry: A Comprehensive Review of Enabling Technologies and Implementation Strategies,” Apr. 01, 2023, *MDPI.* doi: 10.3390/s23083938.

[7] J. F. Yao, Y. Yang, X. C. Wang, and X. P. Zhang, “Systematic review of digital twin technology and applications,” Dec. 01, 2023, *Springer.* doi: 10.1186/s42492-023-00137-4.

[8] W. Li, H. Zhou, Z. Lu, and S. Kamarthi, “Navigating the Evolution of Digital Twins Research through Keyword Co-Occurence Network Analysis,” Feb. 01, 2024, *Multidisciplinary Digital Publishing Institute (MDPI).* doi: 10.3390/s24041202.

[9] I. F. Iumanova, P. V. Matrenin, and A. I. Khalyasmaa, “Review of Existing Tools for Software Implementation of Digital Twins in the Power Industry,” Oct. 01, 2024, *Multidisciplinary Digital Publishing Institute (MDPI).* doi: 10.3390/inventions9050101.

[10] S. Werbińska-Wojciechowska, R. Giel, and K. Winiarska, “Digital Twin Approach for Operation and Maintenance of Transportation System—Systematic Review,” Sep. 01, 2024, *Multidisciplinary Digital Publishing Institute (MDPI).* doi: 10.3390/s24186069.

[11] C. Ge and S. Qin, “Digital twin intelligent transportation system (DT-ITS)—A systematic review,” Dec. 01, 2024, *John Wiley and Sons Inc.* doi: 10.1049/itr2.12539.

[12] T. D. Moshood, G. Nawanir, S. Sorooshian, and O. Okfalisa, “Digital twins driven supply chain visibility within logistics: A new paradigm for future logistics,” Jun. 01, 2021, *MDPI AG.* doi: 10.3390/asi4020029.

[13] K. Wang *et al.*, “Smart Mobility Digital Twin Based Automated Vehicle Navigation System: A Proof of Concept,” *IEEE Transactions on*

Intelligent Vehicles, vol. 9, no. 3, pp. 4348–4361, Mar. 2024, doi: 10.1109/TIV.2024.3368109.

[14] Z. Tang, D. Zhuang, and J. Zhang, “Evaluation framework for domain-specific digital twin platforms,” *Sci Rep*, vol. 15, no. 1, Dec. 2025, doi: 10.1038/s41598-024-82154-8.

[15] A. K. Ramasubramanian, R. Mathew, M. Kelly, V. Hargaden, and N. Papakostas, “Digital Twin for Human-Robot Collaboration in Manufacturing: Review and Outlook,” *Applied Sciences (Switzerland)*, vol. 12, no. 10, May 2022, doi: 10.3390/app12104811.

[16] I. Abdullahi, H. Larijani, D. Liarokapis, J. Paterson, D. Jones, and S. Murray, “A Data-Intelligence-Driven Digital Twin Framework for Improving Sustainability in Logistics,” *Applied Sciences (Switzerland)*, vol. 15, no. 2, Jan. 2025, doi: 10.3390/app15020601.

[17] N. S. Madusanka, Y. Fan, S. Yang, and X. Xiang, “Digital Twin in the Maritime Domain: A Review and Emerging Trends,” May 01, 2023, *MDPI*. doi: 10.3390/jmse11051021.

[18] B. Gerlach, S. Zarnitz, B. Nitsche, and F. Straube, “Digital Supply Chain Twins—Conceptual Clarification, Use Cases and Benefits,” *Logistics*, vol. 5, no. 4, Dec. 2021, doi: 10.3390/logistics5040086.

[19] F. Hakimi, T. Khaled, M. Al-Kharaz, A. C. F. Gouabou, and K. Amzil, “Towards a Digital Twin Modeling Method for Container Terminal Port,” in *Procedia Computer Science*, Elsevier B.V., 2024, pp. 3113–3121. doi: 10.1016/j.procs.2024.09.361.

[20] H. Fatorachian, H. Kazemi, and K. Pawar, “Enhancing Smart City Logistics Through IoT-Enabled Predictive Analytics: A Digital Twin and Cybernetic Feedback Approach,” *Smart Cities*, vol. 8, no. 2, Apr. 2025, doi: 10.3390/smartcities8020056.

[21] A. Dorofeev, V. Kurganov, N. Filippova, A. Petrov, D. Zakharov, and S. Iarkov, “Improving Transportation Management Systems (TMSs) Based on the Concept of Digital Twins of an Organization,” *Applied Sciences (Switzerland)*, vol. 14, no. 4, Feb. 2024, doi: 10.3390/app14041330.